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THE EFFECTS ON MINE VENTILATION OF SHAFT-BOTTOM VANES AND IMPROVEMENTS IN AIRCOURSES

BY

CLOYDE M. SMITH

ILLINOIS COAL MINING INVESTIGATIONS COÖPERATIVE AGREEMENT

(THIS REPORT WAS PREPARED UNDER A COÖPERATIVE AGREEMENT BETWEEN THE ENGINEERING EXPERIMENT STATION OF THE UNIVERSITY OF ILLINOIS AND THE ILLINOIS STATE GEOLOGICAL SURVEY)

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I. Introduction

1. *Object and Scope of Investigation.*—The greatest opportunities for effecting economies in mine ventilation lie, as a rule, in those parts of the mine where the air is forced to move with the greatest speed. This is usually in the aircourses leading from the airshaft, and this region is called the "high-velocity zone" in this report.

In spite of the general knowledge by mining men of the correctness of this statement, it is seldom that they have an adequate appreciation of the magnitude of the possible economies in terms either of reduction of mine resistance, or of dollars and cents. The reason for this lack of appreciation is due largely to the scarcity of exact data gained by careful investigation before improvements were begun and after they were completed. Clean aircourses, free from obstructions and debris, are considered desirable, and some efforts are made regularly or at intervals to attain this end. But whether clean aircourses really pay, or whether this is just a mere theory, has not been clear in the minds of many mine officials. Cleaning aircourses adds to the daily cost sheet, and apparently increases the mining cost per ton of coal. The saving is effected in the power cost and is not credited to the underground management. Thus it is little wonder that the improvement of conditions usually requires a special appropriation.

It was with the hope of presenting indisputable evidence of the economy resulting from improvements in aircourses that this investigation was undertaken. It was believed that additional data of value regarding air flow in mines would be secured as well. The summer season of 1931 was spent in studying the effects of cleaning, enlarging, and otherwise improving the aircourses in the high-velocity zone at a large Illinois coal mine.

The work was done by the methods which had been developed and used in previous ventilation researches.* First, a survey was made of conditions as they existed at the beginning of the work. This was followed by a similar survey after the improvements had been completed. Each survey involved the large-scale mapping of the aircourses to determine their physical characteristics, and the measure-

*University of Illinois, Engineering Experiment Station Bulletins 158, 170, 184, and 199.

ment of air quantities and pressure drops for different conditions of flow.

The zones which were improved and studied in detail consist of a length of nominally straight entry, a T split with a regulator in one branch, and a square bend at the bottom of the intake shaft compartment. The improvements consisted in cleaning the fallen debris and timbers from the aircourse, the replacement of the original regulator by one with an adjustable central discharge opening, and the enlargement of the shaft bottom outlet. As a final step, a set of deflecting vanes was installed in the shaft bottom to aid in changing the course of the air from vertical to horizontal.

2. *Acknowledgments.*—The full coöperation of the mine staff was largely responsible for the success of the work, which was carried on under a coöperative agreement between the Engineering Experiment Station of the University of Illinois and the Illinois State Geological Survey as a part of the regular work of the Engineering Experiment Station, of which DEAN MILO S. KETCHUM is the director, and of the Department of Mining Engineering of which PROF. ALFRED C. CALLEN is the head.

The author was assisted by MR. CLYDE S. SMITH in the underground work and in the subsequent reduction of data.

II. PHYSICAL CHARACTERISTICS

3. *Fan and Coursing of Air.*—The mine is ventilated by a double-inlet centrifugal fan which is 5 ft. wide and 12 ft. in diameter. It is belt-connected to a three-phase, 2200-volt slip-ring induction motor, which has a variable-speed control. The fan has forward-curved blades and is operated blowing.

It discharges horizontally into a short fan drift. From here the air flows down one compartment of the airshaft, at the bottom of which it discharges into the Main West aircourse. This is a single entry, 30 ft. in length, which is intercepted by a North South entry. At the intersection, which forms a T split, the air is divided into two currents, one going south and eventually east into the main producing territories, the other serving the remainder of the mine to the north and west. The south split is the open split, the division of the air between the two splits being artificially controlled by a regulator near the mouth of the north split. The details of the aircourses adjacent to the shaft before and after alterations are shown in Figs. 1 and 2, respectively.

4. *Shaft Bottom.*—The intake, or downcast, compartment of the airshaft is concrete-lined from top to bottom. Its cross-sectional dimensions are 8.0 by 12.5 ft., the longer axis lying north to south. The depth of the shaft, from the fan drift floor to the sump, is 218 ft. The sump is shallow and the small amount of water which drips into it from the shaft drains through a small pipe into the sump in the hoisting compartment.

Plan and profile views of the shaft bottom as it was at the beginning of the work are given in Fig. 1, which includes a series of cross-sectional diagrams of the Main West aircourse into which the shaft discharges. From the profile view it is clear that the shaft outlet was severely restricted by debris on the floor of the aircourse.

While the cross-sectional area at section 0+09W,* under the west shaft wall, was 79.0 sq. ft. that at section 0+16W was but 64.9 sq. ft. The average cross-sectional area of the Main West aircourse is estimated at 71 sq. ft. Aside from constrictions in cross-sectional area, the roof and floor of the Main West aircourse were very irregular. This is indicated in the profiles of Fig. 1, and in Fig. 3, which is a view of the Main West aircourse from the shaft bottom as it was at the start of the work.

In addition to removing the loose debris from the entry, during the course of alterations, the average roof level was raised about three feet and the floor lowered from 2 to 3 ft. This not only added from 5 to 6 ft. to the height of the aircourse, but gave it smoother roof and floor profiles. This is shown in Fig. 2, which corresponds with Fig. 1, but represents post-alteration conditions. The mean cross-sectional area of the Main West aircourse is now estimated at 131 sq. ft., an increase over the former mean area of nearly 85 per cent. To match the enlarged cross-section of the entry, the sump was cleaned and a part of the bottom of the west shaft wall was blasted away, giving the shaft outlet the hexagonal shape shown in section 0+09W, of Fig. 2. The cross-sectional area of this section is 113.0 sq. ft. Figure 4 is a view of the shaft bottom after the alterations had been completed.

5. *Split and Regulator.*—The termination of the Main West aircourse at its intersection with the Main North South entry, as shown in Figs. 1 and 2, forces the incoming air to divide into two opposite currents. Before alterations the regulator which limits the quantity going north was at the mouth of the Main North aircourse and dis-

*The letters following plusses in the text refer to the entry in which the cross-section referred to is located, as follows: W = Main West aircourse; S = Main South aircourse; N = Main North aircourse.

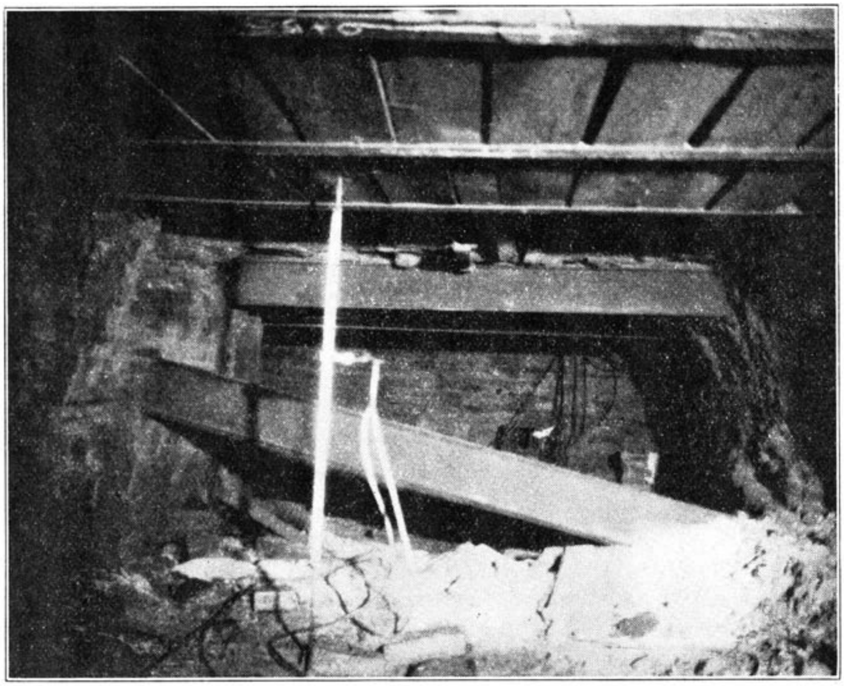

FIG. 3. MAIN WEST AIRCOURSE FROM SHAFT BOTTOM, BEFORE ALTERATION

charged mainly at its east end, as shown in Figs. 1 and 5. The latter is a view of the regulator taken from the north. It also shows the general character of the roof and floor in this entry. A short distance inbye the regulator the entry assumed a highly restricted cross-section due to a large accumulation of debris along the east rib. This is shown by the cross-section diagrams of Fig. 1. The intersection proper was partly obstructed by timbers, although it had more height than the adjoining parts of the North South entry. Due to the presence of top coal, the height of the Main South aircourse averaged only about 5 ft. for the first 50 ft. or so. This gave that part of the entry a mean cross-sectional area of about 50 sq. ft., while that of the Main North entry, inbye the regulator, was but 40 sq. ft.

As shown in Fig. 2, cleaning these entries smoothed their profiles and increased their height a great deal. The mean cross-sectional area of the Main South aircourse, near the intersection, was enlarged to more than 90 sq. ft., an increase of about 80 per cent over the original area. In the Main North entry the mean cross-sectional area was more than doubled.

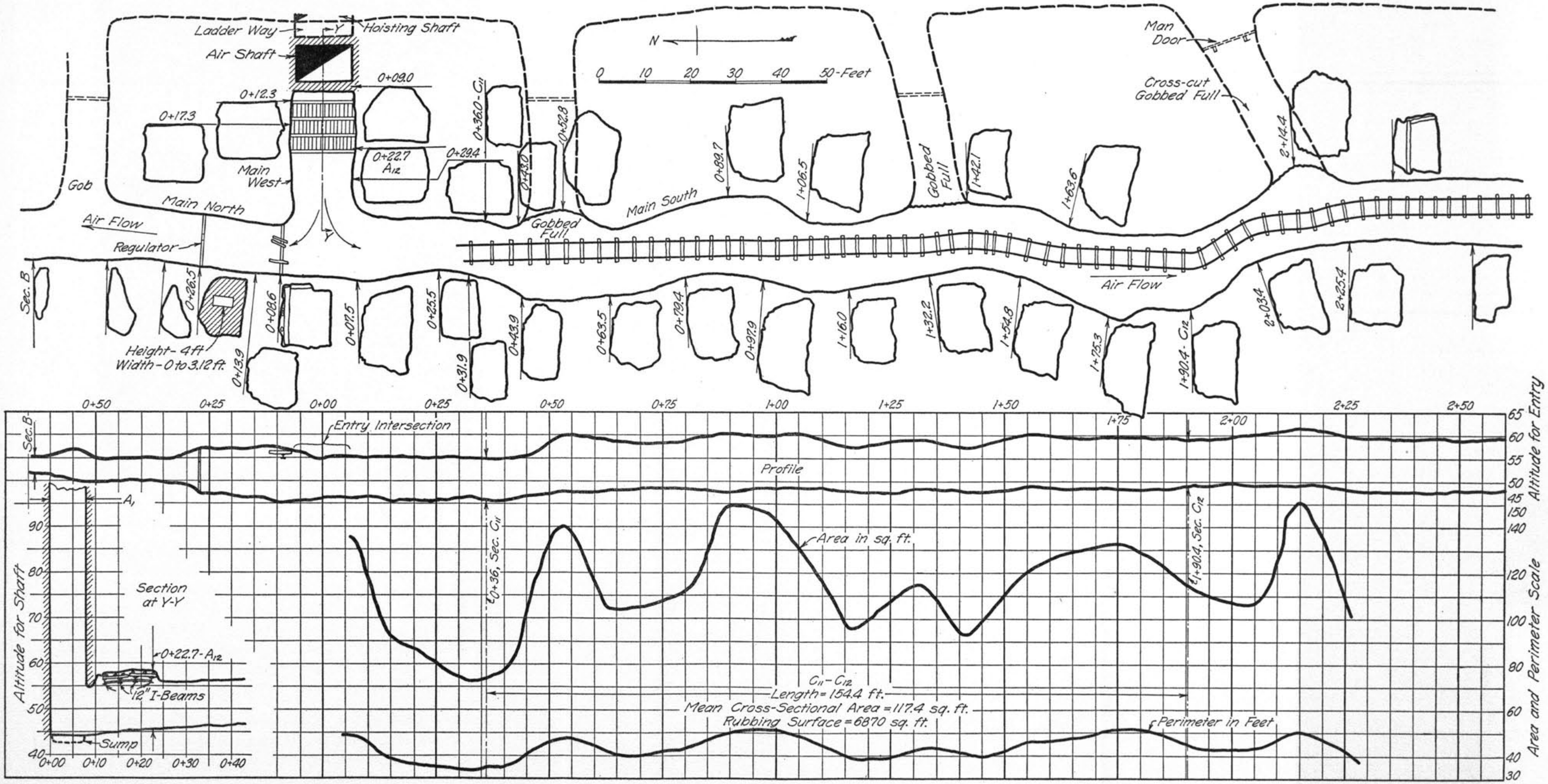

Fig. 2. Plan and Profile of Aircourses Adjacent to Shaft, After Alteration

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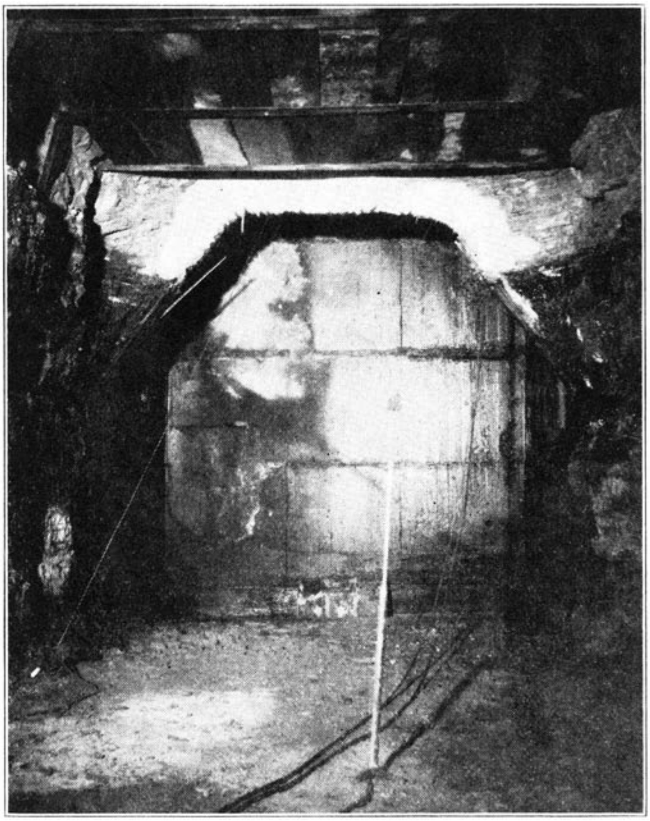

Fig. 4. Shaft Bottom, After Alteration

A new regulator was built in the Main North aircourse at section 0+26.5N, as shown in Fig. 2. It is equipped with a centrally located slide door, which permits adjustment of the width of opening between the limits of no opening and one 3.12 ft. wide. The height of the opening is fixed at 4.0 ft. As the construction of the regulator was imperfect, there is some leakage around and through it. The Main North aircourse was not cleaned inbye the new regulator, so that its physical characteristics remained unchanged beyond that point.

6. *Straight Entry.*—The first 200 ft. of the Main South aircourse gave an opportunity to measure the effects on airflow of cleaning a length of nominally straight entry. The desirable length was limited by a change in the type of roof support farther inbye, and by audible leakage at some of the stoppings which would have been included in

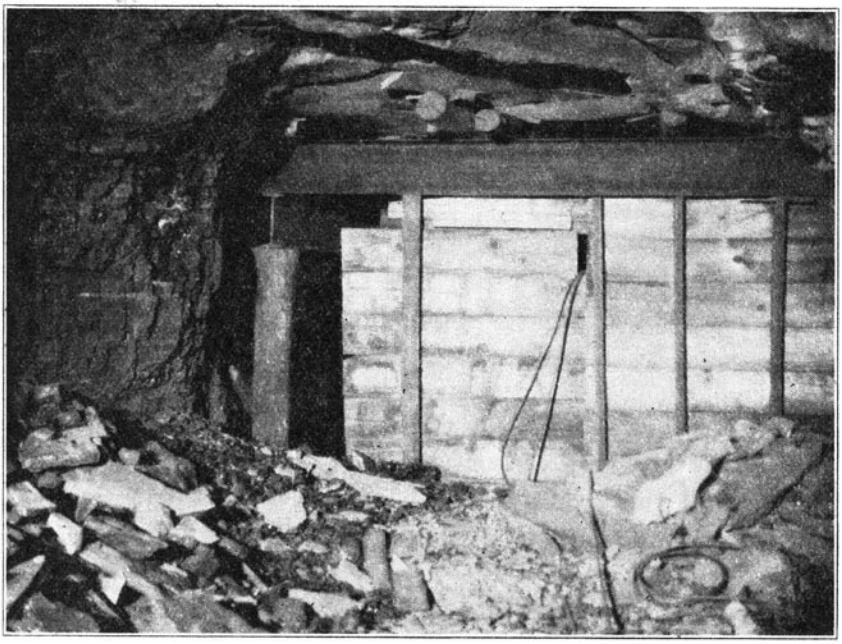

FIG. 5. REGULATOR FROM NORTH, BEFORE ALTERATION

additional lengths of entry. As to the original character of the chosen part of the aircourse, Fig. 1 shows that the restricted height which prevailed in the first 50 ft. gradually increased to 7 or 8 ft. from about 1+00 to 1+90S. Debris on the floor reduced the height to about 5 feet at 2+05S. From here it gradually increased again. The plan shows that, while the entry was nearly uniform in width, it was quite crooked from about 1+50 to 2+00S. Figure 6 is a view looking upstream (north) through section C3 (2+12S).

Comparing Fig. 2 with Fig. 1, it is seen that by the cleaning of the entry the height and width have been increased considerably. While the floor profile has been much improved, the roof profile is still rather irregular, and the plan of the entry is considerably more crooked than formerly. This is due to the fact that all loose coal and debris were removed from the pockets in the ribs, thereby accentuating the irregularity of the rib lines. This variability in ribs and roof leads to a greater variability in cross-sectional area, as shown by a comparison of the area curves of Figs. 1 and 2. There was a 54-per-cent increase in the mean cross-sectional area of this part of the aircourse, from an average of approximately 76 to 117 sq. ft.

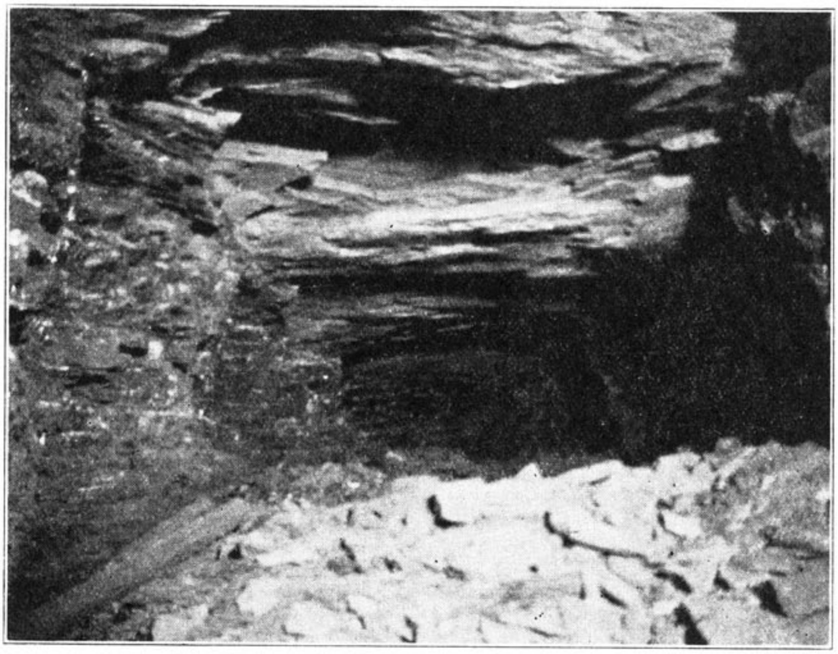

FIG. 6. MAIN SOUTH AIRCOURSE, LOOKING NORTH THROUGH SECTION C3, BEFORE ALTERATION

III. PRESSURE MEASUREMENTS AND QUANTITY DETERMINATIONS

7. *Pressure Measurements.*—Air quantities and static pressure differences were determined by the methods previously described,* the Ellison gage being relied on for all pressure measurements. At the beginning of the work a traverse section was established in each of the three aircourses, Main West, Main North, and Main South. These were designated sections A2, B, and C1, respectively, their locations and outlines being shown in Fig. 1. Each of these sections was used as a static pressure section as well as a traverse section, and additional static pressure sections were established as needed. One of these, section C3 at 2+12.0S, terminated the straight entry zone which began at section C1 (0+35.3S). Another, section A1, was established in the downcast compartment of the shaft, 51.5 ft. above the sump. A pitot tube was mounted in this section by suspending a piece of 2 by 4-in. lumber diagonally across the shaft and mounting

*Bulletin 158, Engineering Experiment Station, University of Illinois.

the tube on it, so that the tube pointed up along, or near, the center line of the shaft.

Section A1 and section B were unchanged by the alterations. As Fig. 2 shows, section A2 was replaced by section A12, which was used as a pressure section only. Sections C1 and C3 were replaced by sections C11 and C12, respectively.

8. *Quantity Determinations.*—The first step in the air measurements was to run three traverses at each of the three traverse sections (A2, B, and C1) with normal airflow. These were accompanied by suitable center-velocity-pressure and static-pressure-drop measurements; the former to establish a relationship between quantity and center-velocity pressure at each section, and the latter to measure the losses incurred in passing the air from section to section. The average normal-airflow quantity for the main current (section A2) was 109 900 cu. ft. per min.; that for the north split (section B) was 48 700, and for the south split (section C1) 61 800 cu. ft. per min. Thus the total average quantity in the splits was 110 500 cu. ft. per min., an excess of less than one per cent over the main current quantity. None of the individual quantities deviated by as much as one per cent from the mean of its group. Additional traverses were run at higher or lower than normal quantities.

The resulting data were used to establish the relation of quantity to center velocity pressure at each section, as shown in Fig. 7, where the quantity is plotted logarithmically against the center velocity pressure, as of standard air density (0.075 lb. per cu. ft.). With a few exceptions, the alinement of the points is good.

Much the same program was carried out after the alterations had been completed, except that the main current was not traversed. Its quantity was gaged by adding the quantities in the north and south splits. These data, coupled with appropriate center velocity pressure readings, were used to establish the post-alteration curves for section A1, shown in Fig. 7. Only two traverses were run after the vanes were installed, both of which were at section C11 in the south split.

Where quantities were determined for all three currents by simultaneous center velocity pressure readings at each traverse section, it is possible to gage their comparative accuracy by checking the sum of the split quantities against the main quantity. More than 40 such comparisons were made. They show that the indicated main quantity tended to exceed the sum of the split quantities by from 1 to 2 per cent, on the average, although there was more variability in these

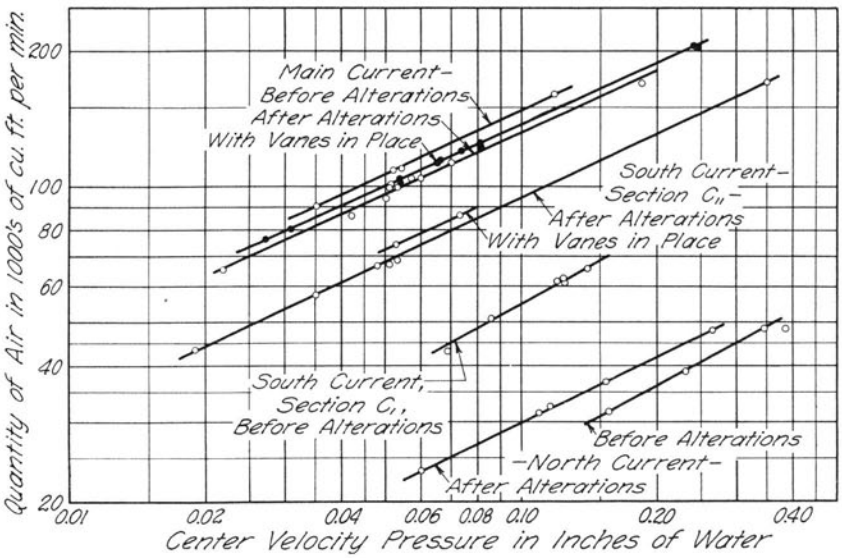

FIG. 7. RELATION OF QUANTITY TO CENTER VELOCITY PRESSURE

discrepancies than in those in which the results of direct traversing were compared. Each set of observations was judged on its own merits, and the quantities adjusted to their most probable values. The adjusted quantities were used in the calculation of losses.

IV. Transmission Losses

A. Before Installation of Vanes

9. *Losses at Shaft Bottom.*—As has been previously stated the losses incurred in passing the air around the 90 deg. bend at the bottom of the shaft were determined by measuring the static pressure drop from section A1, in the shaft, to section A2, in the Main West aircourse, before alterations (Fig. 1) and from section A1 to section A12 after alterations (Fig. 2). Thus the static pressure drops, as measured, include the drop due to about 40 ft. of shaft and 15 ft. of entry, in addition to the drop due to the bend itself. Ordinarily, in computing bend losses, a deduction is made for the estimated frictional losses incurred in the approach to and departure from the bend, but inasmuch as the primary concern in this case was to determine the effect of alterations on the losses in the high velocity zone no such deduction* has been made. Hence the calculated savings are

*The deductions can readily be calculated, for a given quantity, by use of the physical data of the passageways given in Figs. 1 and 2. It is necessary to assume suitable values of k for the shaft and entry, of course.

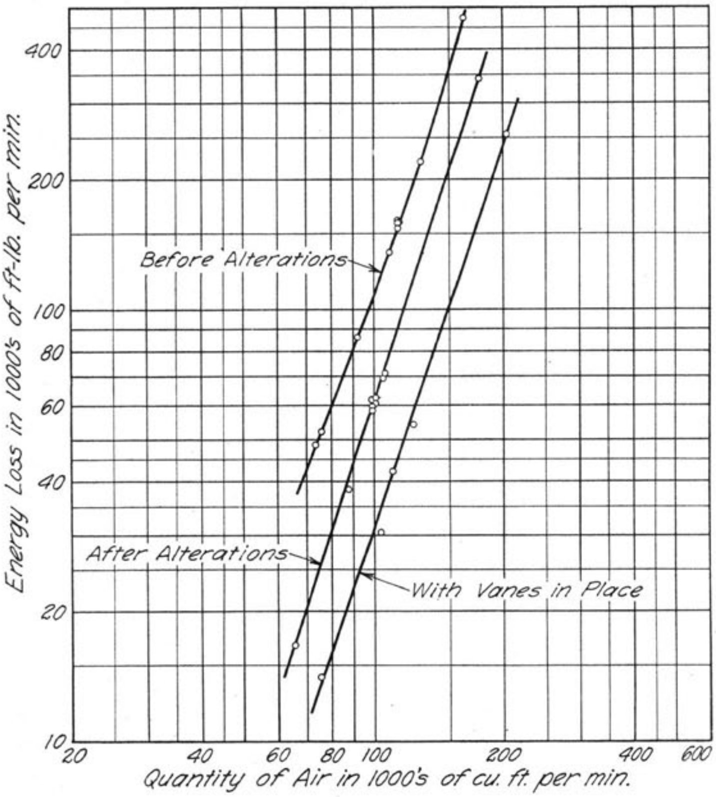

Fig. 8. Energy Loss at Shaft Bottom Bend

a full, rather than a partial, measure of the benefits which resulted from the alterations.

Nine static pressure drop measurements were made before alterations and eleven after. The relation of energy loss to quantity, before and after alterations, is shown in the upper two curves of Fig. 8. It is evident that the alterations effected an appreciable saving. For a normal quantity of 110 000 cu. ft. per min. this is as follows:

	Total Pressure Loss in. of water	Energy Loss air horsepower*
Before alterations........	0.243	4.21
After alterations.........	0.140	2.42
Reduction...............	0.103	1.79

*By the term "air horsepower" is meant the loss of energy in the air stream, in horsepower, as distinct from losses in mechanical or electrical energy at the fan or its driving mechanism.

This is a 42-per-cent reduction in the losses around the shaft bottom bend.

The ratio of the total pressure loss to the mean-velocity pressure* in the shaft averaged 3.42 before alterations but only 1.86 after alterations. Similarly, the specific resistance† fell from 0.201 to 0.116.

10. *Losses at Split and Regulator.*—The positions of the regulators (Figs. 1 and 2) were such that it was necessary to take the pressure measurements in the north split some distance downstream from them. This makes it impossible to segregate the losses due to the regulator from the splitting losses for the north current. The splitting losses themselves include losses from two or more sources which are inseparable. One of these is the loss incurred in cleaving the main current into two subsidiary currents. Another is the loss arising from deflecting each of the split currents through a 90-deg. angle. For present purposes of determining the effects of alterations, a third source, the frictional losses in the approaches to and departures from the pressure measuring sections will be included, although it would be possible to estimate these losses with a fair degree of accuracy and make deductions for them.

Since losses at a split have not been reported before, it seems worth while to reproduce one of the tables used in calculating the losses and characteristics of the combined split and regulator. Table 1 shows the loss determinations that were made at the split and regulator before alterations. These were made under varied conditions of flow at total quantities ranging from 74 000 to 162 800 cu. ft. per min. The normal quantity ranged from 109 700 cu. ft. per min., when the mine was working, to 115 000 cu. ft. per min., in one instance, when it was idle. Under these conditions the static pressure drop from section A2 in the main current to section B, beyond the regulator in the Main North aircourse, averaged 1.35 in. of water, while the static pressure drop from section A2 to section C1 in the Main South aircourse averaged about 0.27 in. of water.

To derive total pressure losses, it is necessary first to assume an arbitrary pressure datum from which the static pressure at each section is expressed. This was done by assuming the static pressure at section B to be zero, whence the static pressure at section A2

*Mean-velocity pressure is to be distinguished from mean velocity-pressure. By the former is meant the velocity pressure which corresponds with the mean velocity of air flow. The latter expression refers to the mean of the velocity pressures actually existing at all points in the cross-section. While theoretically, the mean velocity-pressure is the desired item, the other is used because of its readier derivation. When the mean velocity-pressure is calculated from traverse data it is necessarily larger than the corresponding mean-velocity pressure. Ordinarily, the discrepancy is relatively small, but instances have been noted in which it was more than one-sixth of the mean-velocity pressure. See also Appendix, Note 1, page 44.

†See Appendix, Note 2, page 45.

TABLE 1

SPLIT AND REGULATOR LOSSES, BEFORE ALTERATIONS

	1	2	3	4	5	6	7
A. General Data							
1. Date, July 1931	1	3	4	4	4	5	5
2. Mine, working or idle	working	idle	idle	idle	idle	idle	idle
3. Approximate fan speed, r.p.m.	153	153	153	153	122	105	153
4. Air coursing	normal	normal	normal	S. shorted	normal	normal	S. shorted
B. Adjusted Quantities (cu. ft. per min.)							
5. Main Current	109 700	113 000	115 000	129 000	91 000	74 000	162 800
6. North Split	48 200	48 700	48 700	46 800	39 000	32 500	40 300
7. South Split	61 500	64 300	66 300	82 200	52 000	41 500	122 500
8. Per cent of Quantity in South Split	56.1	56.9	57.6	63.7	57.1	56.1	75.3
C. Pressures (in. of water)							
9. Mean-Velocity Pressure at Section A2 (Main Current)	0.152	0.161	0.167	0.210	0.105	0.069	0.335
10. Mean-Velocity Pressure at Section B (North Split)	0.281	0.287	0.287	0.265	0.184	0.128	0.196
11. Mean-Velocity Pressure at Section C1 (South Split)	0.094	0.102	0.109	0.167	0.067	0.043	0.372
12. Static Pressure Drop A2-B	1.35	1.35	1.37	1.26	0.901	0.610	1.16
13. Static Pressure Drop A2-C1	0.279	0.264	0.272	0.394	0.164	0.120	0.888
14. Sectional Total Pressure A2	1.502	1.511	1.537	1.47	1.006	0.679	1.495
15. Sectional Total Pressure B	0.281	0.287	0.287	0.265	0.184	0.128	0.196
16. Sectional Total Pressure C1	1.165	1.188	1.207	1.033	0.804	0.533	0.644
17. Total Pressure Loss A2-B	1.221	1.224	1.250	1.205	0.822	0.551	1.299
18. Total Pressure Loss A2-C1	0.337	0.323	0.330	0.437	0.202	0.146	0.851
19. Overall Total Pressure Loss	0.726	0.712	0.718	0.717	0.467	0.324	0.962
D. Energy Loss (ft. lb. per min.)							
20. Energy Loss A2-B	306 000	310 000	316 000	293 000	166 500	93 200	272 000
21. Energy Loss A2-C1	108 000	108 000	113 500	187 000	54 600	31 500	542 000
22. Overall Energy Loss	414 000	418 000	429 500	480 000	221 100	124 700	814 000
E. Split-Bend-Regulator Characteristics							
23. Specific Resistance A2-B	5.27	5.17	5.28	5.50	5.40	5.22	8.00
24. Specific Resistance A2-C1	0.892	0.783	0.752	0.647	0.748	0.848	0.567
25. Overall Specific Resistance	0.602	0.561	0.543	0.432	0.563	0.592	0.363

Explanation:

Line 4; S = south split.

Lines 9-11 = $0.0000000624 \left(\frac{Q}{A}\right)^2$ where Q = quantity and A = cross-sectional area of pressure section.

for line 9, A = 70.3 square feet, Q of line 5
for line 10, A = 22.7 square feet, Q of line 6
for line 11, A = 50.2 square feet, Q of line 7

Lines 12 and 13 = Average of field measurements, as of standard air density = 0.075 lb. per cu. ft.

Lines 14-16 are based on an assumed static pressure datum of 0 at Section B.

line 14 = line 9 + line 12
line 15 = line 10
line 16 = line 11 + line 12 − line 13

Line 17 = line 14 − line 15; line 18 = line 14 − line 16; line 19 = $\frac{\text{line 22}}{5.2 \times \text{line 5}}$.

Line 20 = 5.2 × line 6 × line 17; line 21 = 5.2 × line 7 × line 18; line 22 = line 20 + line 21.

Line 23 = $\frac{\text{line 17} \times 10^{10}}{(\text{line 6})^2}$; line 24 = $\frac{\text{line 18} \times 10^{10}}{(\text{line 7})^2}$; line 25 = $\frac{\text{line 19} \times 10^{10}}{(\text{line 5})^2}$.

becomes the static pressure drop A2-B1, or line 12 of Table 1. The static pressure at section C1 is the difference between that at section A2 and the static pressure drop A2-C1, or line 12 − line 13. The total pressure at a given section is, of course, the sum of its static pressure and its mean-velocity pressure (lines 9-11). These total pressures are

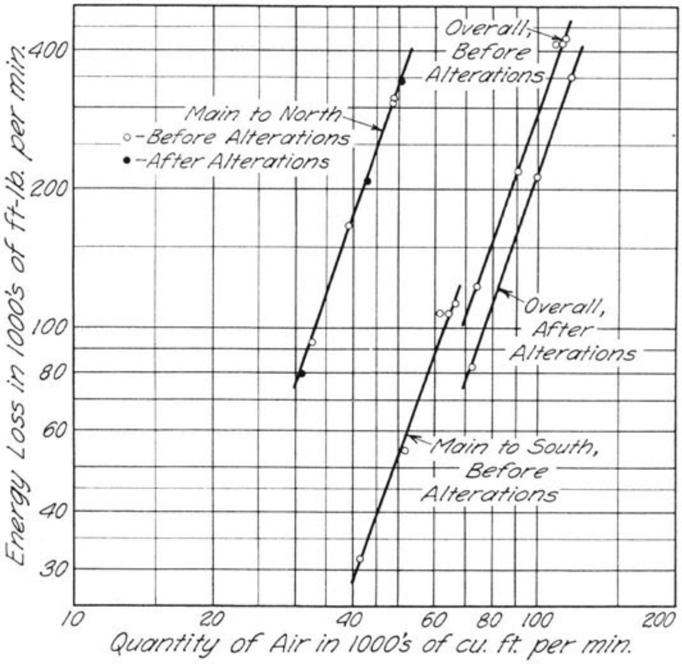

FIG. 9. SPLIT AND REGULATOR LOSSES, BEFORE AND AFTER ALTERATION

shown in lines 14-16. The total pressure loss into the north split is the difference between the total pressures at sections A2 and B and, similarly, that into the south split is the difference between total pressures at sections A2 and C1. The normal pre-alteration total pressure loss through the regulator was 1.22 in. of water, and that around the south split and bend 0.33 in. of water.

Since only a part of the total mine quantity is subject to either of these total pressure losses, the overall total pressure loss must be calculated by weighting the partial losses in total pressure by their respective quantities. This is most easily done by using the overall energy loss of line 22, which is the sum of the partial energy losses (lines 20 and 21). The energy losses for normal aircoursing are plotted against their corresponding quantities in Fig. 9. Aside from a few erratic points, the alinement is good. The north split gives by far the highest losses, quantity for quantity, due to the regulator. An interesting feature of these curves is that both of the split curves lie above the overall energy loss curve. This means that to pass a given quantity of air through either split alone would cause a greater loss than to divide it between the two splits in the proportions (56.8 per cent south, line 8) which these curves represent.

After the alterations had been completed near the shaft bottom, and the new regulator installed in the Main North aircourse it was found that nearly the same relative distribution of air as formerly was got with a regulator opening 4.0 feet high and 3.0 feet wide. At this width of opening 57.4 per cent of the air went south instead of 56.8 per cent, as previously. While there was an excess of 0.6 per cent to the south after alterations, the agreement is close enough to indicate the effects of the alterations on the losses in the split and regulator. The north split and overall results have been added to Fig. 9. For the north split the points fall along the pre-alteration loss curve, but for the south split they were less than 1/10 as great as they formerly had been, quantity for quantity, and are not shown in Fig. 9. This relatively great saving around the south split-bend resulted in an appreciable overall saving as indicated below, for a quantity of 110 000 cu. ft. per min.

	Total Pressure Loss in. of water	Energy Loss air horsepower
Before alterations........	0.664	11.50
After alterations.........	0.484	8.39
Reduction..............	0.180	3.11

This is a 27-per-cent reduction in losses, which is considerably less than the 42-per-cent reduction effected at the shaft bottom. However, the absolute savings are actually larger than they were at the shaft bottom, because of the larger losses involved. Coupled with the reduction at the shaft bottom they give total savings of 0.283 in. of water, and of 4.90 air horsepower in getting the air out of the shaft and into the splits. The improvements in the splitting zone are reflected in lowered specific resistances. That of the south split-bend was reduced from 0.805 to 0.065 while the overall specific resistance of the split and regulator fell from 0.57 to 0.40.

11. *Regulator Characteristics.*—The adjustability of the regulator opening gave an opportunity to determine its characteristics as affected by the width of opening, fan speed, etc. The relation of total pressure loss* to quantity is shown in the lower part of Fig. 10. The straight lines represent the behavior of total pressure loss with respect to quantity for a given size of opening, as indicated. The area

*Since no comparison of pre- and post-alteration conditions was involved in analyzing the characteristics of the new regulator, the estimated split-bend losses from west to north plus the estimated friction losses between the regulator and Section B, in the Main North, were deducted from the measured losses, leaving the net losses of Fig. 10, which are regarded as being due to the regulator only.

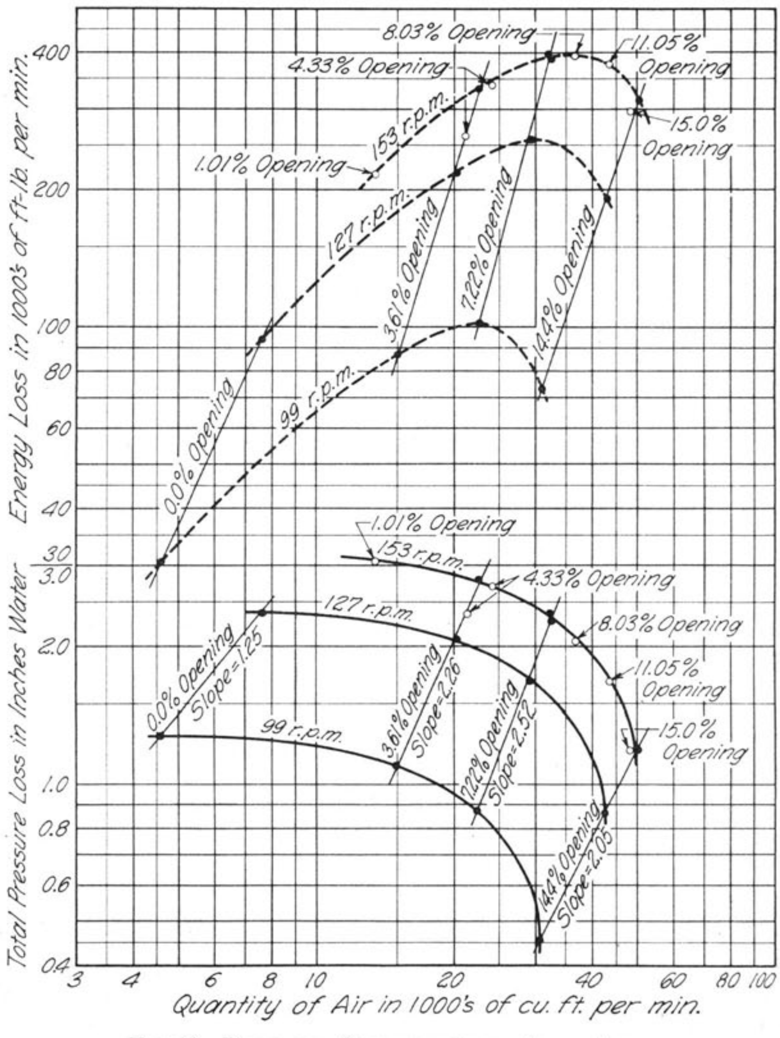

FIG. 10. REGULATOR CHARACTERISTICS, AFTER ALTERATION

of the opening is expressed as a per cent of the overall area of the regulator, 83.1 sq. ft. For each opening the quantity was controlled by changing the fan speed, the approximate values of which are indicated along the curved lines.

The fact that an appreciable quantity of air flowed with the slide door closed (zero opening) shows that the regulator leaked somewhat. However, the amount of leakage must decrease rapidly with increased

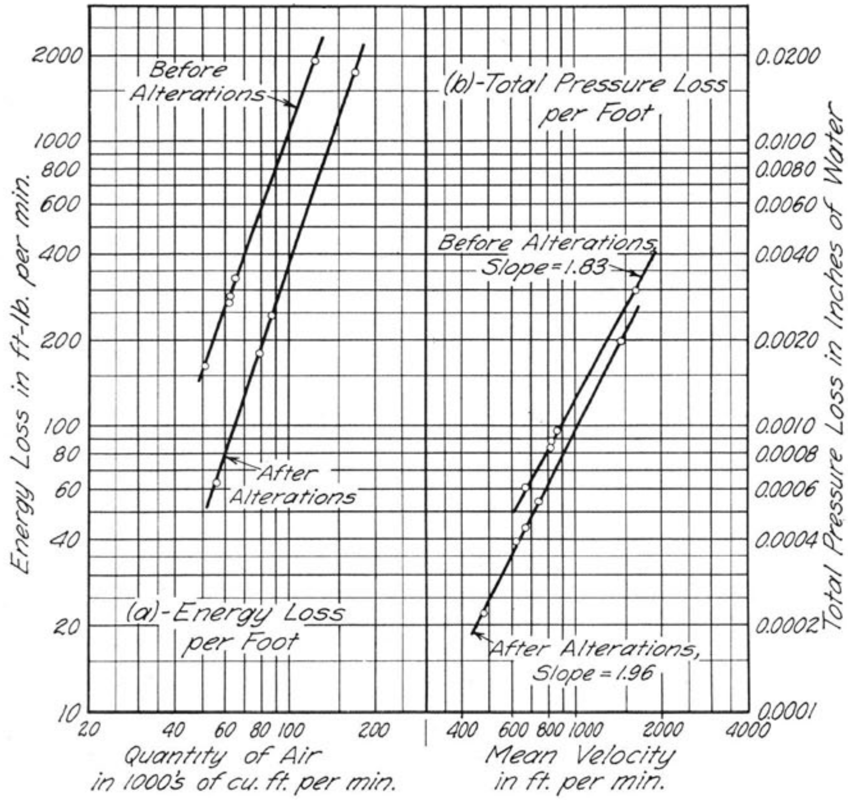

FIG. 11. LOSSES IN STRAIGHT ENTRY

opening, so that its effects are less marked at the larger openings. The slopes of the straight lines vary from 1.25 with the door closed to 2.52 with a 7.22-per-cent opening. At 14.4-per-cent opening, the slope exceeded the conventional value of 2.00, by 3 per cent.

Each curved line in the lower part of the figure shows how the total pressure loss varied with quantity at a given fan speed with different widths of opening. The curves fall with increasing rapidity as the quantity increases; so that to increase the quantity from 10 000 to 20 000 cu. ft. per min. at a given fan speed reduces the total pressure loss about 13 per cent, but to increase it further from 20 000 to 40 000 cu. ft. per min. reduces the total pressure loss approximately an additional 40 per cent.

This rapid relative decrease in total pressure loss with increasing quantity has an interesting effect on the energy loss caused by the regulator. This is shown in the upper part of Fig. 10, where the energy loss is plotted against quantity. For a given fan speed the energy loss rises to a maximum, then drops rapidly away, as the quantity is increased by opening the door. The decline is due to the fact that the total pressure loss decreases at a higher rate than that at which the quantity increases. The result is that the energy loss, which is proportional to the product of the two, decreases. In this case the maximum energy loss was incurred at about 7- to 8-per-cent opening. At this setting the total pressure loss was 71 per cent of the total pressure loss at zero opening. These results agree with those previously obtained* at an adjustable regulator in another mine. However, since both regulators are known to have leaked, the agreement may be partly accidental, although it is logically necessary that a regulator have a setting of maximum energy loss. This is because it develops no energy loss at either of its extreme settings, zero opening and 100 per cent opening; hence the energy loss must reach a maximum at some intermediate setting. At present, the data are too meager to generalize as to where this may be expected to fall in a given case.

12. *Losses in Straight Entry.*—The losses in the straight entry zones in the Main South aircourse are shown in Fig. 11. The energy loss per foot of entry is plotted against quantity in part (*a*). The following comparison is made for a normal quantity of 61 500 cu. ft. per min. which prevailed in this split before alterations:

	Total Pressure Loss per Foot in. of water	Energy Loss per Foot ft. lb. per min.
Before alterations........	0.00086	275
After alterations.........	0.00027	88
Reduction...............	0.00059	187

While these savings seem small, they represent a two-thirds reduction in the losses in a certain length of entry, at a given quantity of air-flow. This is the largest relative saving effected in the high-velocity zone. However, since the mean cross-sectional area of the aircourse was more than 50 per cent larger after alterations than it had been before, most of the saving is due to the lessened velocities at which a given quantity of air is transmitted. A better criterion of the comparative conditions of flow prevailing before and after alteration is the relation of total pressure loss to mean velocity. This is

*Unpublished data.

shown in part (*b*) of Fig. 11. While an improvement in flow is shown by the fact that the post-alteration line lies under the pre-alteration line, the two curves are much closer to each other than are those of part (*a*). That this indicates a lower relative saving in total pressure loss per foot of entry at like mean velocities than at like quantities is shown in the following comparison, which is made at a mean velocity of 800 ft. per min. This was nearly the normal value before alterations.

	Total Pressure Loss per Foot in. of water
Before alterations	0.00083
After alterations	0.00063
Reduction	0.00020

This represents about a 24-per-cent decrease in total pressure loss, per foot of entry, at like mean velocities, as compared with a 68-per-cent reduction at like quantities. Thus it is evident that by far the major part of the savings which resulted from cleaning the aircourse was due to the reduction in speed of transmission rather than to improved lines of flow.

Since large savings were effected by cleaning a portion of the South split, which is unregulated, the question arises as to whether or not corresponding savings could be effected by cleaning the North split, inbye the regulator. As any savings effected by cleaning a regulated aircourse must be counteracted by reducing the regulator opening to maintain the same rate of flow, nothing is to be gained by improving the aircourse.

One slight exception might be taken to this statement where the regulator is placed near the beginning of the current which it controls, as is the case in the North split. To clean an aircourse inbye the regulator so situated would reduce the pressure difference between it and the return entry, and thereby reduce the leakage through the stoppings. While this would effect a saving, a better, and probably more economical remedy would be to repair the leaky stoppings.

A point is sometimes overlooked in placing regulators. They should be put as far outbye in the split as practicable so that the stoppings between the aircourse and the adjacent entry will be under a lower pressure difference than if the regulator were farther inbye. This keeps the inevitable leakage through the stoppings at a minimum, provided that the stoppings are well constructed.

An interesting feature of Fig. 11 is the difference in the slope of the pre-alteration and post-alteration lines. Referring to the curves of part (*b*), the slope of the pre-alteration line is 1.83 while that of the post-alteration line is 1.96, a little less than the conventional value of 2.00. Since the changes in cross-sectional area and perimeter were both more frequent and more severe after alterations than before (compare Figs. 1 and 2) it may be that the increased slope of the loss curves is due to the greater prevalence of conversion, that is, expansion and contraction losses, as distinct from frictional losses. Further investigation would be required to determine this point.

The commonly accepted criterion of flow in straight entries is the coefficient of friction k from the Atkinson formula for resistance $5.2\,ia = klo\,v^2$, which needs no explanation. At normal quantities k averaged 141×10^{-10} before alterations and 134×10^{-10} after alterations. The latter figure largely fails to reflect the 24-per-cent improvement in air flow, previously noted. The reason for this lies in the formula, which, transposed to the form $k = \dfrac{5.2\,i\,a}{lov^2}$, shows k to be proportional to $\dfrac{a}{o}$ as well as to $\dfrac{i}{v^2}$ for a given length of entry. The ratio of cross-sectional area to perimeter $\dfrac{a}{o}$ is known as the "hydraulic radius" r. If the ratio $\dfrac{i}{v^2}$ be regarded as the desired criterion of quality of flow, it may be expressed in familiar terms by dividing k by r since $\dfrac{i}{v^2} \propto \dfrac{k}{r}$. The mean hydraulic radius in the Main South aircourse increased from 2.10 to 2.64 ft. as a result of the alterations, so that the ratio $\dfrac{k}{r}$ fell from 67.1×10^{-10} to 50.8×10^{-10}, a decrease of 24 per cent. This agrees with the improvement in airflow previously deduced from the total loss curves and shows that the ratio must be used as a flow criterion, rather than k alone, where an appreciable difference in the size of the passageways is involved.

13. *Fan Characteristics and Power Consumption.*—The normal fan speed throughout this work was 153 r.p.m., although it varied within a per cent or two from time to time, under changing conditions of load and power supply. At this speed the fan was normally delivering about 110 000 cu. ft. per min. against a recording static water gage of 3.3 in., as of standard air density. Adding to this the mean-velocity pressure of 0.07 in. in the fan drift gives a total water gage of 3.37 in. Thus the energy imparted to the airstream by the fan was 58.4 h.p.

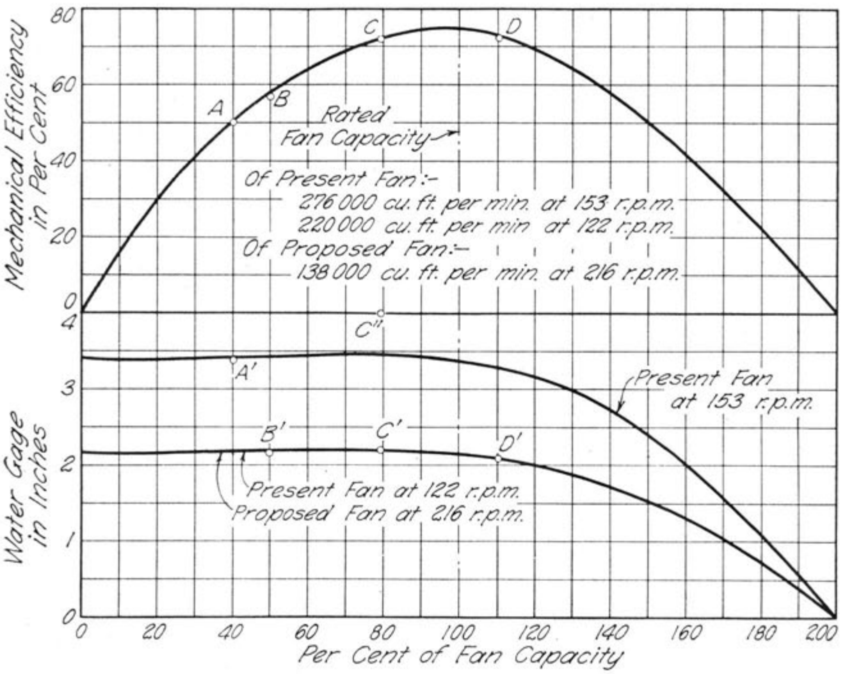

FIG. 12. FAN CHARACTERISTICS

Under these conditions, readings of the fan watt-hour meter showed a power consumption of 133 h.p. so that the overall efficiency was but 43.9 per cent. The rated capacity of the fan at 153 r.p.m. is 276 000 cu. ft. per min., so that it was operating at about 40 per cent of its rated capacity. According to the manufacturer's characteristic curves for this fan its mechanical efficiency at this capacity is 50 per cent, whereas it reaches 75 per cent at full capacity. These curves are shown in Fig. 12 where water gage and mechanical efficiency are plotted against the per cent rated capacity of the fan. A water-gage curve is shown for each speed at which the fan was operated. Points A and A' represent the pre-alteration efficiency and water gage, respectively. B and B' are the corresponding post-alteration points.

At the beginning of the work, the specific resistance of the mine was 2.8. Since the cleaning program was not completed until after the close of the season's work, it is impossible to say what mine resistance was finally attained, but from partial data at hand it is thought to be about 1.8. At any rate it was decreased* to such an

*With the vanes in place in the shaft bottom, their effect being blended with the effect of cleaning the aircourses.

extent that the normal fan speed could be reduced to 122 r.p.m. This brought the recording water gage down to 2.1 in. and is thought to have left the quantity about as it formerly was. Under these conditions the average daily power consumption of the fan motor was 1340 kw-hr., which is at the rate of 74.8 h.p. As its output was 37.6 air h.p., the overall fan-drive efficiency was about 50 per cent. The fan was then operating at about 50 per cent capacity, its rated capacity at 122 r.p.m. being 220 000 cu. ft. per min. At this relative capacity its mechanical efficiency is 57 per cent (point *B*, Fig. 12); 7 per cent higher than the former operating efficiency.

The fact that the fan has been operating at from only 40 to 50 per cent capacity shows that it is too large for the mine by a considerable margin. This means that it is operating on the rising part of its efficiency curve (Fig. 12) so that any increase in its relative capacity, up to 100 per cent, results in an increase in its efficiency. Thus, the increase in fan efficiency between points *A* and *B* resulted from the decrease in mine resistance which permitted the fan to operate at a greater relative capacity. If the fan had originally been operating at more than its rated (100 per cent) capacity, the decreased mine resistance would have resulted in a lower fan efficiency.

At this mine the alterations resulted in savings from two different sources: first, the inevitable savings from the improvement of the entries as air conductors; second, an incidental saving from increased fan efficiency.

As to the fan itself, a similar fan of one-half the capacity would be amply large. Such a fan would have a diameter of $\frac{12}{\sqrt{2}} = 8.5$ ft. and a width of 3.54 ft. Its normal rating would be 138 000 cu. ft. per min. at 216 r.p.m. against a 3.4-in. water gage. Such a fan would deliver the present mine quantity of about 110 000 cu. ft. per min., against a 2.2-in. water gage (point *C'*, Fig. 12). Under these conditions the fan would be operating at 79.7 per cent capacity and 72.5 per cent efficiency (point *C*) as compared with the present efficiency of about 50 per cent. The change in fans would reduce the power consumption of the fan motor nearly one-third.

Within certain limits, expansion in the ventilating requirements of the mine could be met without reducing the efficiency of the proposed fan below 72.5 per cent. This might be done in either of two ways, or by a combination of both. One is to increase the fan speed without changing the mine resistance. This has the effect of raising the water gage without affecting the relative capacity of the fan, or its efficiency. For example; the fan would deliver 110 000 cu. ft. per min. against a 2.2-in. water gage but if 150 000 cu. ft. of air per min. were to be delivered against the present mine resistance, the fan would have to be speeded from 216 to 294 r.p.m. ($216 \times \frac{150\,000}{110\,000} = 294$). Its rated capacity at this speed is 188 000 cu. ft. per min., of which the delivered quantity represents 79.7 per cent, as stated. Thus the efficiency would remain at 72.5 per cent (point C) but the water gage would rise to 4.0 in. (point C''). The power consumption of the fan motor would increase from 52.5 to 130.5 h.p., nearly a 150 per cent increase.

The other way to provide a greater quantity would be to reduce the mine resistance to such an extent that the fan could deliver the required quantity without being speeded up. This could be done by improving the entries, re-coursing the air, etc., so as to keep the mine resistance at a minimum.

In the case of the proposed fan operating at 216 r.p.m., it would be necessary to reduce the water gage against which the fan operates to 2.1 in. (point D'), to induce a quantity of 150 000 cu. ft. per min. to flow through the mine. The fan would then be operating at 108.7 per cent capacity and at 72.5 per cent efficiency (point D) as before.

Its power consumption would be 68.5 h.p. This is to be contrasted with 130.5 h.p. which would be consumed in delivering the same quantity simply by speeding up the fan. A saving of 72 h.p. is to be had from improving the mine air flow.

14. *Ventilation Costs and Economies.*—When the work was undertaken the average daily power consumption of the fan motor was 2340 kw-hr., about 12 per cent of the total consumption at the mine on a working day. After the alterations had been completed, and the fan slowed, its average daily power consumption was reduced to about 7 per cent of the average working-day power consumption for the whole mine. For a month of 18 working and 12 idle days, the pre-alteration fan power consumption averaged 16.6 per cent of the total power consumption, while the corresponding post-alteration figure is 10.6 per cent, a reduction of 6 per cent of the total power consumption, during a normal working month.

The reduction amounted to 1000 kw-hr. per day. At 1.5 cents per kw-hr., this represents a saving of \$15 daily, or \$5470 annually.* Since the total cost of the improvements which permitted this saving to be made was about \$3700, they paid for themselves in the first

*An additional saving resulted in the form of reduced demand charges.

eight months. A liberal estimate of the cost of maintaining the entries in their present condition is 20 per cent of the cost of the summer's work, during which the accumulation of several years' debris was removed from the entries. This amounts to $740 per year, leaving a net annual saving of $4730, which is equivalent to a net return of 128 per cent annually on the money recently expended.

During the course of the work, 2500 ft. of aircourse were cleaned at a cost of $1.40 per ft. Figure 11 shows that, at a quantity of 61 500 cu. ft. per min., which is about the normal quantity in the south split, the energy loss per foot of entry was 187 ft. lb. per min. less after alterations, than before. This is 0.0057 air h.p. which, at 50-per-cent fan-drive efficiency, is 0.0114 electrical h.p. At a cost of $100 per horsepower-year which is nearly equivalent to 1.5 cents per kw-hr., the annual power saving becomes $1.14 per ft. of entry. Deducting the estimated maintenance cost of $0.28 per ft. from the saving in power cost leaves a net estimated annual saving of $0.86 per ft. of entry, or 61.5 per cent of the cost of cleaning the aircourses. However, in calculating the per foot cost of cleaning the straight entries, the total cost of cleaning, $3500, was divided by the length of entry cleaned, so that the straight entries bore all the cost, whereas much of the savings were effected at the split, bends, regulator, etc. This accounts for the fact that the average net annual return for the mine as a whole was 128 per cent, while it was only 61.5 per cent in the straight entries. They were charged with all costs but were not credited with savings at the split, bends, etc.

These savings will be reviewed briefly in terms of dollars and cents, assuming a fan-drive efficiency of 50 per cent. At the split, with 61 500 cu. ft. per min. going south and 48 500 north, the alterations effected a saving of 3.11 air h.p., which is equivalent to 6.22 electrical h.p., or $622 annually. At the shaft bottom the saving at 110 000 cu. ft. per min. was 1.79 air h.p., equivalent to $358 annually. Thus cleaning the aircourses immediately tributary to the shaft resulted in an annual power saving equivalent to nearly $1000, within 100 ft. of air travel.

However, four-fifths of the total power saving was made in the great length of aircourse which was cleaned beyond the shaft bottom zone. This entry included a 90-deg. deflection, an overcast, and some highly restricted portions with other irregularities, so that savings were at a higher rate, per foot, than that measured in the Main South aircourse. Reducing all of the savings realized in this 2400-ft. length

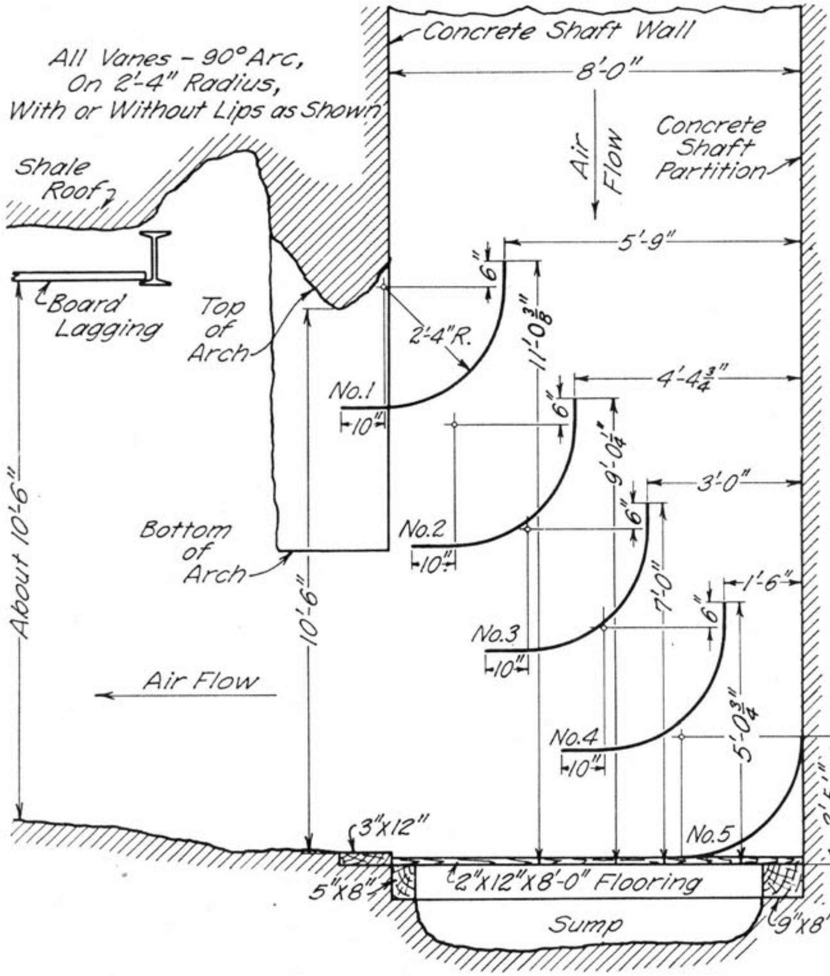

Fig. 13. Section of Vanes in Shaft Bottom

of aircourse to a unit basis gives an indicated annual power saving equivalent to \$1.80 per ft. of entry.

This shows that, to realize the maximum benefits from a program of this kind, the high-velocity open split or splits must be improved from end to end.

B. With Vanes in Place

15. *The Vanes.*—The design of the vanes which were installed in

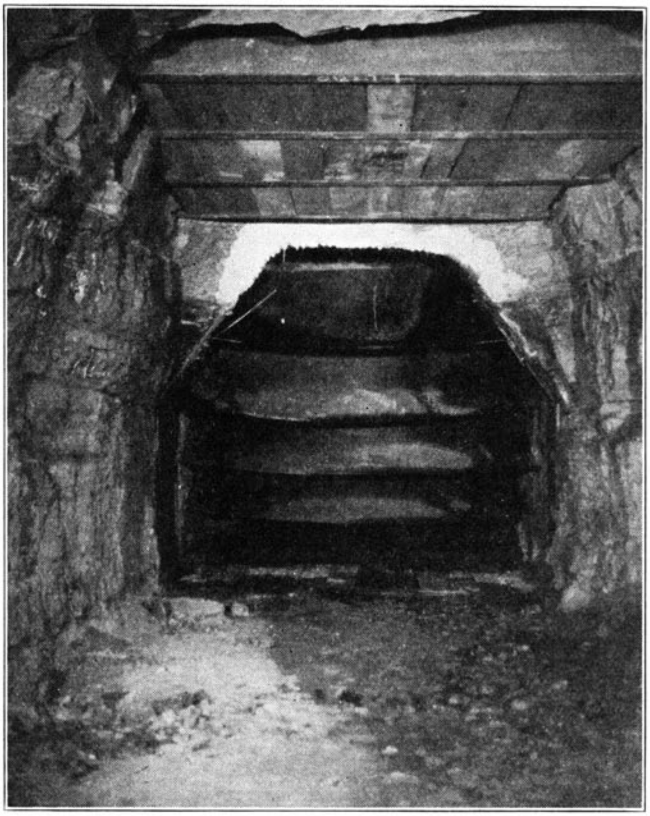

FIG. 14. VANES VIEWED FROM MAIN WEST AIRCOURSE

the shaft bottom followed, in a general way, that which has been developed for the design of blade elbows in industrial ducts.*

However, these principles of design were not directly applicable because of differences in shape and cross-sectional area between the shaft and the Main West aircourse, differences of a kind not provided for in the design referred to. By using average dimensions, and consideration for available materials of construction, the following design was arrived at:

Four vanes, each consisting of a 90-deg. arc on a 28-in. radius with a 6-in. vertical lip in the shaft and a 10-in. horizontal lip in

*Wirt, H. L., "New Data for the Design of Elbows in Duct Systems," General Electric Review, Vol. 30, pp. 286-296, June, 1927, and other data.

the entry. These vanes to be spaced along the diagonal from the upper central point of the outlet arch to the heel of the shaft bottom. Material: 16-gage blue annealed sheet metal.

One lipless vane to round off the lower back corner. Material: 24-gage galvanized iron.

Each vane to reach across the long axis (12.5 ft., north to south) of the shaft and to be supported at each end by an angle iron bolted to the shaft wall. $2\frac{1}{2} \times 2\frac{1}{2}$-in. angle irons were used.

The location of the vanes is shown in Fig. 13. A larger intake area was allotted to vane No. 1 than to any of the others in an attempt to get a due proportion of the air to flow over it. To have set No. 1 vane so as to include but one-fifth of the shaft area might have left it with considerably less than one-fifth of the volume, for two reasons: (a) the velocities along the walls and near the corners are presumably lower than those in the central part of the shaft, and (b) the outlet of No. 1 vane is partly obstructed by the sloping arch shoulders (Fig. 14). In fact, it was necessary to notch the two lower corners of this vane to accommodate these shoulders.

In installing the vanes the supporting angle irons were cut to length, drilled, and bent to shape, and the flat sheets were cut and drilled to match the angles on the surface. After the angles had been fastened to the shaft walls, by one-inch expansion bolts, the sheets were bolted to them, working from top to bottom. The sheets were gradually drawn into shape as the work progressed. Irregularities in the shaft walls reduced the distance between corresponding angle irons below the design distance to such an extent as to cause each vane to bend back somewhat along the top edge and down along the bottom edge. The effect of the bulges is to discharge part of the air which issues above each vane at a downward angle, instead of horizontally. This probably impairs the effectiveness of the vanes to some extent. Figure 14 is a view of the vanes in place, taken from the Main West aircourse.

The total cost of the vanes, installed, is estimated as follows:

Cost of Materials		$76
Cost of design and fabrication		31
Cost of installation:		
Cleaning shaft bottom, 4 men 1 shift	$25	
Installing vanes, 4 men 1 shift	$25	
Supervision, power, and misc	$30	80
Total cost of vanes installed		$187

16. *Bend Characteristics.*—The characteristics of the shaft bottom bend as affected by the vanes are reviewed below:

	Ratio of Total Pressure Loss to Mean-Velocity Pressure in Shaft	Specific Resistance
After alterations		
Before vanes installed.....	1.86	0.116
With vanes in place......	0.93	0.058
Reduction...............	0.93	0.058

While this is a 50-per-cent reduction, analogy with industrial applications* indicates that considerably more than a 50-per-cent reduction in the losses at a bend can be effected by vanes. Whether this can be accomplished under the adverse conditions commonly prevailing in mines must be determined by further experimentation.

17. *Transmission Losses and Savings.*—The relation of energy loss around the shaft bottom bend to quantity, with the vanes in place, is shown in Fig. 8. The line lies well below that representing the losses before the vanes were installed. Comparison is made at a quantity of 110 000 cu. ft. per min., as follows:

	Total Pressure Loss in. of water	Energy Loss air horsepower
After alterations		
Before vanes installed	0.140	2.42
With vanes in place...	0.071	1.23
Reduction.......	0.069	1.19

The saving in power consumption is equivalent to $238 annually. Deducting 20 per cent of the cost of the vanes as the estimated annual cost of maintenance leaves a net saving of about $200 per year, which is more than the cost of the vanes. At present the annual saving is probably less than this, due to the fact that the formation of ice in the shaft in the coldest months necessitates the temporary removal of the vanes. This fault is not inherent in the vanes, of course, and would not arise in a dry shaft, nor in any shaft serving an exhausting fan.

In considering all of the savings estimated in this report, it should be borne in mind that they are based on present normal quantities, which are moderate for a large mine. Were the quantity of air flowing

*Wirt, op. cit.

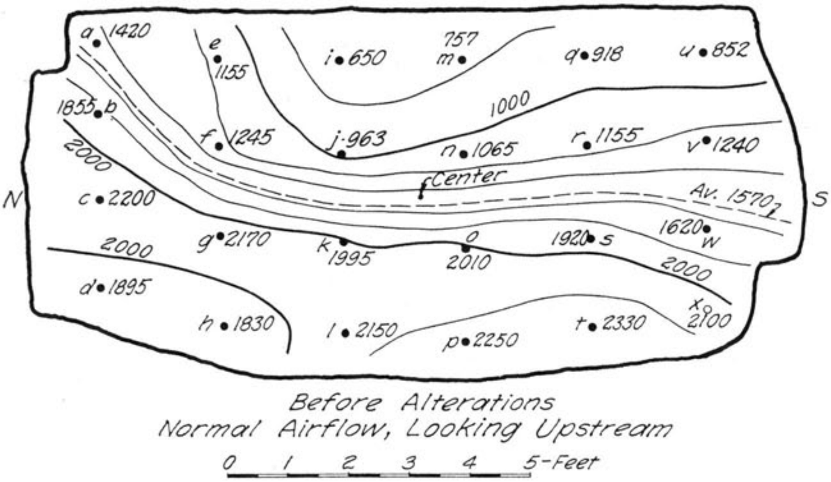

FIG. 15. ISOVEL DIAGRAM, SECTION A2, BEFORE ALTERATION

to be increased, the savings would mount rapidly, as the power consumption varies about as the cube of the quantity, and the net savings would increase in virtually the same proportion.

V. CHARACTERISTICS OF AIR FLOW

18. *Velocity and Pressure Distributions.*—The isovel* diagrams for the four traverse sections reveal some interesting characteristics of the air flow in the high-velocity zone. A typical one for section A2, in the Main West aircourse before alterations, is shown in Fig. 15. It represents a traverse which was run while the mine was working. The diagram shows that the lowest velocities prevailed in the central upper part of the section, around points *i* and *m*, while the highest velocities were found in the bottom row around points *p* and *t*. The maximum velocity was more than 3.5 times the minimum. The mean velocity curve (1570 ft. per min.) lies at about mid-height in the south two-thirds of the section, but rises sharply toward the upper north corner.

The velocity distribution at this section has some similarity with those found at other mines in the aircourse near the downcast shaft bottom. One of these† has been previously illustrated. Except at low fan speed, it shows a prevalence of high velocities near the floor,

*See Univ. of Ill. Eng. Exp. Sta. Bul. 158, p. 63, 1926.
†Univ. of Ill. Eng. Exp. Sta. Bul. 184, Fig. 4, p. 10, 1928.

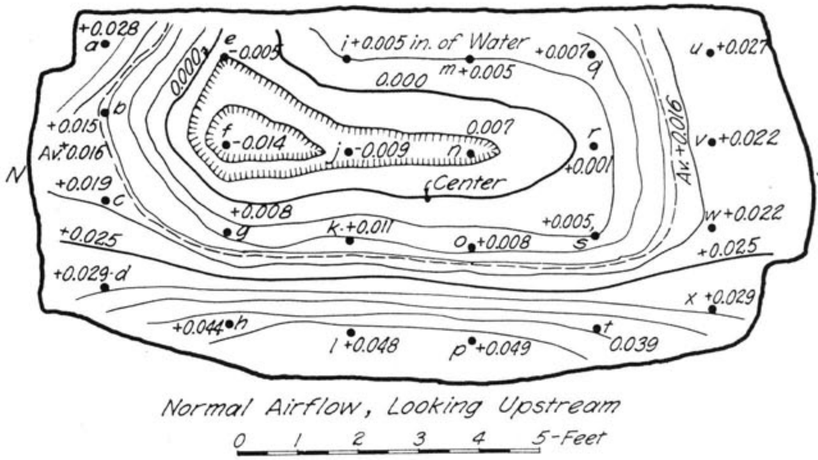

FIG. 16. ISOSTAT DIAGRAM, SECTION A2, BEFORE ALTERATION

and an upper central low-velocity region, as in Fig. 15. The existence of high velocities near the floor is to be expected from the tendency of the air to impinge on the floor of the sump and to flow into the entry from there. The explanation of the low velocities in the upper central region is less obvious.

During the traverse represented by Fig. 15, readings were taken to give the static pressure drop between the traverse point and the center. The results are shown in Fig. 16, in which lines have been drawn through points of equal static pressure. Hence the diagram is referred to as an isostat diagram. The center is arbitrarily taken as the datum of zero pressure. In the hachured region above and to the left of the center, the pressure was less than at the center. Elsewhere, save on the zero-pressure line, it was greater. The extreme range in intra-sectional static pressures was 0.063 in. of water, which is 41 per cent of the mean-velocity pressure in the section. The mean sectional static pressure was 0.016 in. of water greater than the static pressure at the center of the section. There seems to be little relation between the isostat and the isovel diagrams; save that, in a broad way, the static pressure was high where the velocity was high, particularly in the lower half of the section. Thus the differences in static pressure tend to augment, rather than to modify, the differences in velocity and in velocity pressure. The result is that the distribution of total pressure throughout the section is more irregular than that of either the velocity or static pressure.

Such inequalities in intra-sectional pressures are characteristic of

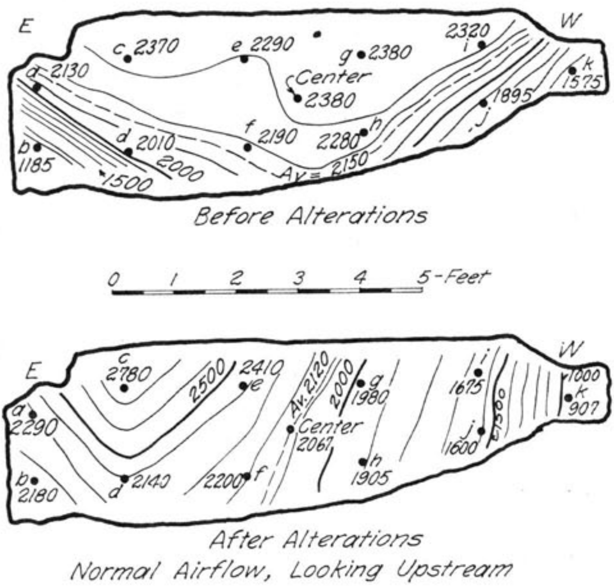

FIG. 17. ISOVEL DIAGRAMS, SECTION B, BEFORE AND AFTER ALTERATION

mine airflow. They have been noted under many conditions of flow, and at mean velocities of the order of 1000 ft. per min. or greater they are usually of such magnitude as to admit of reasonably accurate measurement. They probably arise from the fact that the momentum of the air tends to carry it in a pre-determined direction through a given cross-section. This prevents the air from responding instantaneously to the transvérse static pressure differences to which it is subject, with the result that such pressure differences are permanently maintained within the cross-section.

Figure 17 shows the velocity distribution in section B, in the Main North aircourse before and after alterations. The broad upper central region of high velocity, which existed before alterations, gave way to a nearly uniform velocity gradient with the velocity decreasing in all directions from point "c" in the upper east part of the section. Since the entry was not changed within about 35 ft. of section B, the difference in velocity distribution is due to differences between the two regulators, both as to location and manner of discharge. It will be recalled that the new regulator was put about 18 ft. closer to section B than the old one, and discharges centrally rather than at one end (see Figs. 1 and 2).

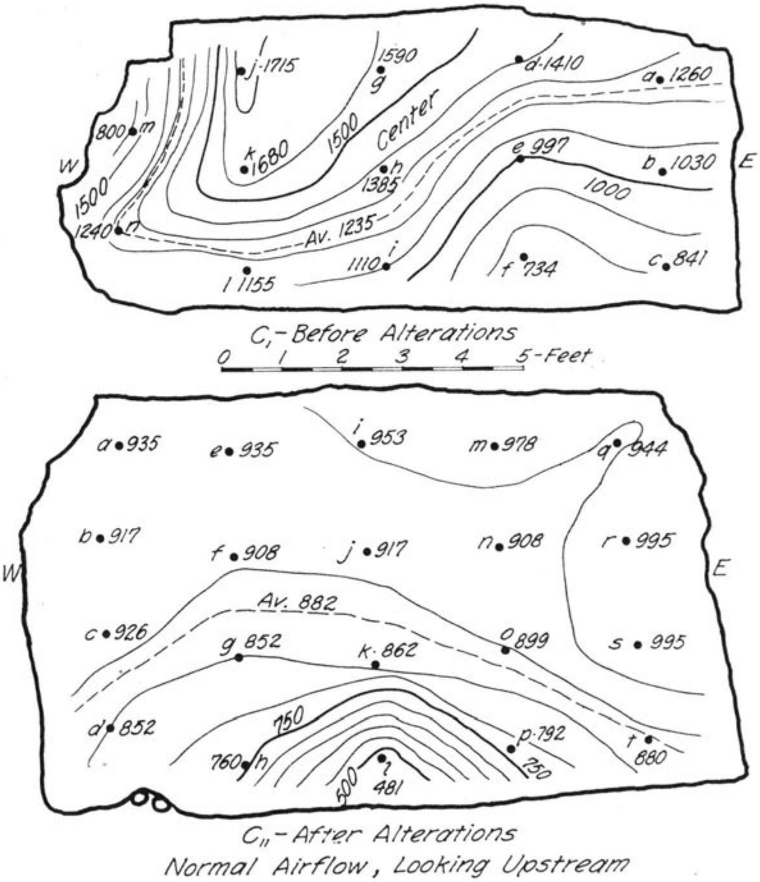

FIG. 18. ISOVEL DIAGRAMS, SECTIONS C1 AND C11, BEFORE AND AFTER ALTERATION

Two different traverse sections were used in the Main South split; section C1 before and section C11 after alterations. While section C11 was located within a foot or two of where section C1 had been, the two sections differed considerably in outlines and in velocity distribution. This is shown in Fig. 18. The pre-alteration diagram shows a pronounced region of high velocity in the upper west part of the section, around points *j* and *k*. Such a shift of the high-velocity focus to the west side of the section might be expected from the fact that the course of the air is deflected from west to south just upstream from section C1. However, with the same deflection in effect after alterations, the high-velocity focus has given way to a widespread distribution of velocities which are only moderately higher than the average, throughout the upper one-half of the section. The air no longer crowds to the west, or outer rib of the bend, because of its westerly momentum, as it formerly did. This change and the sharp reduction in losses around the south split-bend, reflect greatly improved flow in this zone.

The new distribution is almost symmetrical about the vertical center line. Velocities are less along the lower half of this line than elsewhere in the section. This gives the diagram the arched effect, which has been encountered previously at several sections, notably at section N2.* The persistence of this type of velocity distribution over a wide variety of sections and mean velocities establishes it as a characteristic phenomenon of airflow which arises under certain conditions. It may be related to the two helices of flow which have been observed in ducts.† Its exact nature and significance await determination.

19. *Center Constants.*—The ratio of the mean velocity in a section to the velocity at its center, called the center constant, was originally developed as a means of determining quantity from center velocity pressure readings. However, since the ratio changes with quantity in many sections, the graphical method of determination illustrated by Fig. 7 is preferred. The center constant decreases with the quantity whenever the slope of the quantity against center-velocity-pressure curve in such a diagram is less than one-half. It increases with the quantity when the slope is greater than one-half. The slope of each line in Fig. 7 is given as item 4 of Table 2. It ranges from 0.56 at section C1, before alterations, to 0.46 at section A1 in the shaft, after alterations. It decreased at all of the sections, due to the alterations.

The magnitude of the center constant is dependent on the velocity distribution within the section. If the velocity at the center of the section is higher than the average velocity, as it normally is, the center constant will be less than one, but if the velocity at the center is lower than the average, the center constant will be greater than one. Its values for the different sections are listed as item 5 of Table 2. They range from 0.875 to 1.195 at sections C1 and A1, respectively, before alterations. The center constant was greater than 1.00 at every section after alterations. This is reflected in Fig. 7, in that the post-alteration lines lie above the corresponding pre-alteration lines,

*See Univ. of Ill. Eng. Exp. Sta. Bul. 170, Fig. 9, p. 61, 1927.
†Wirt, op. cit., Fig. 7.

TABLE 2

CENTER CONSTANTS

	Main Current	North Split	South Split
1. Approximate Normal Quantity (cu. ft. per min.)	110 000	48 500	61 500
2. Section			
a. Before Alteration	A1*	B	C1
b. After Alteration	A1	B	C11
3. Cross-sectional Area of Traverse Section (sq. ft.)			
a. Before Alteration	100	22.7	50.2
b. After Alteration	100	22.7	76.0
4. Slope of Quantity vs. Center Velocity Pressure line†			
a. Before Alteration	0.47	0.54	0.56
b. After Alteration	0.46	0.48	0.47
5. Center Constant $\left(\frac{V_m}{V_c}\right)$			
a. Before Alteration	1.195	0.91	0.875
b. After Alteration, before vanes	1.07	1.02	1.01
c. Vanes in Place	1.12	....	1.065

*All center velocity pressure readings referred to in this column were taken at Section A1, in shaft. However, this current was traversed at Section A2 before alterations only.

†Plotting logarithm of quantity against logarithm of center velocity pressure, Fig. 7.

with the exception of section A1, in the shaft. Here the center constant fell from 1.195 before alterations to 1.07 after alterations, then rose to 1.12 when the vanes were installed.

Since no traversing could be done at section A1, the center constant gives the only clue to its velocity distribution. The fact that it was greater than one, shows that lower than average velocities were occurring at the center; whereas a higher center velocity would be expected from the regular character of the shaft. This abnormal velocity distribution may be due to influences either from above, where the air enters the shaft, or from below, where it leaves. That the physical characteristics of the shaft bottom did influence the velocity distribution at section A1 is shown by the change in center constant which resulted from each change at the shaft bottom.

20. *Lines of Flow.*—The approximate lines of flow of the air were visualized by holding a 6-in. piece of light cotton cord, which had been tied to a small brass tube about three feet long, at different points in the air stream. The observer's body was kept as well downstream from, and to one side of, the string as practicable. The indications of this device are thought to be reasonably reliable, except at low velocities. While its chief utility is in indicating the direction of flow, its behavior gives some clue to comparative air speeds as well.

The lines of flow were traced around the shaft bottom bend, before

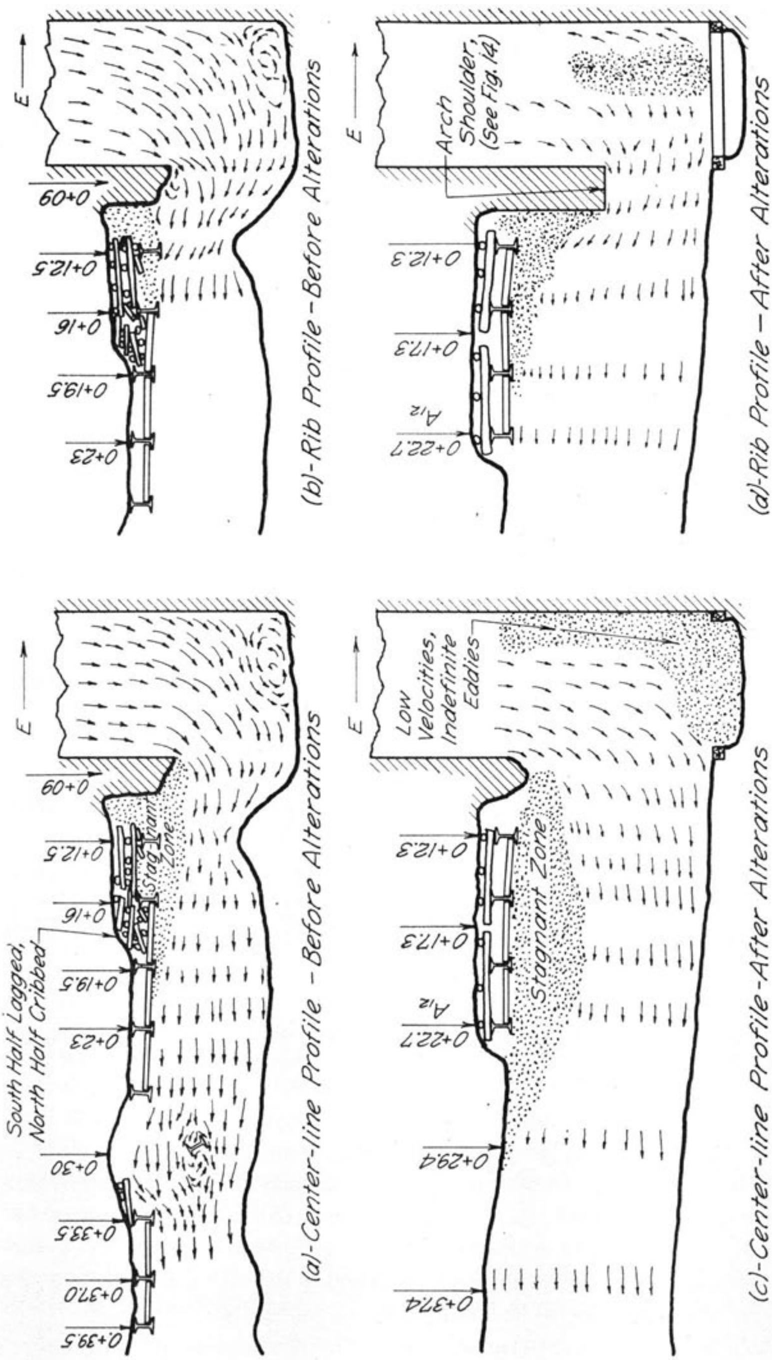

FIG. 19. LINES OF FLOW, AROUND SHAFT BOTTOM BEND, BEFORE AND AFTER ALTERATION

and after alterations, with the general results indicated in Fig. 19. The pre-alteration flow was characterized by a downward motion throughout the shaft cross-section, above the brow of the outlet. Below this the air rapidly acquired a horizontal component. A small eddy at moderate velocities occupied the "heel" of the shaft bottom as indicated in Fig. 19. Parts (*a*) and (*b*) of this figure show a characteristic difference between the manner in which the air escaped from the central part of the shaft bottom and from near the ribs. In the former case, a rather large zone of stagnation or mild eddying existed for some distance just west of and above the brow, while near the ribs the air had such an upward component on leaving the shaft as almost to fill the aircourse. This left a much smaller zone of eddying and stagnation than in the upper central part of the entry. The greater velocities persisted in the roof corners for some distance from the shaft, and were apparent in section A2. This is shown by the isovel diagram (Fig. 15).

The central post-alteration flow is indicated in part (*c*) of Fig. 19. While it is essentially like the pre-alteration flow, see part (*a*), it had much larger zones of stagnation, both in the upper central part of the entry and in the shaft bottom. The small heel eddy shown in part (*a*) has become a large zone of stagnation and indefinite eddying which occupies the sump and reaches well up into the shaft along the back shaft wall. Enlarging the outlet led to much lower velocities, of course, and this apparently encouraged the development of stagnant zones in spaces in which the air had previously been forced to move progressively.

It has been suggested* that the resistance around the shaft bottom bend could have been reduced by installing a shield in the upper part of the entry, to conform with the envelope of the stagnant zone as indicated in Fig. 19c. This would have made a venturi elbow like those used in industrial ducts where structural features do not permit rounding the inner corner. In spite of their restricted cross-section, such elbows are more efficient than plain elbows. However, rounding of the inner corner is to be preferred to either the square or the venturi elbow.

Part (*d*) of Fig. 19 shows the flow of air near the ribs, after alterations. In addition to the prevalence of slowly rising currents in the back shaft corners, it differs from the central flow much as did the pre-alteration rib flow. The chief difference is that the air escapes from the shaft with a pronounced upward component which leads to a

*Prof. A. P. Kratz, Department of Mechanical Engineering, University of Illinois, personal communication.

considerable reduction in the size of the stagnant zone at the roof near the shaft. This is a little surprising, since the escape of air near the ribs is not only retarded by the frictional resistance of the surfaces, but is obstructed by the sloping shoulder of the arch (Figs. 2 and 4). However, it is probable that the slower velocities with which the rib currents enter the shaft bottom permit them to change direction more quickly and thus to seek the low-pressure regions in the entry more directly than can the central currents, which have greater downward momenta to be overcome.

The development of such large zones of stagnation and eddying after alterations suggests that the savings effected around the shaft bottom bend may have been due entirely to reduction in air velocities in the entry, rather than to improved lines of flow.

With the vanes in place, the flow of air throughout the shaft bottom was greatly improved. Each vane delivered air into the entry at high velocities along its upper surface and, with minor exceptions, the interspaces were well utilized by progressive flow. Slight stagnation and re-entry were noted just under vanes 1 and 2 (Figs. 13 and 14). It is probable that the intake areas for vanes 2 and 3, which underlie these spaces, are too small to provide good velocities throughout the interspaces.

That velocities are much higher than formerly in the upper part of the entry is shown by the fact that some of the water which dripped down along the west shaft wall was carried into the North-South entry, whereas, before the vanes were installed, the drippings all fell within a few feet of the shaft.

The splitting of the air at the entry intersection seemed to proceed smoothly, along normal lines. The presence of the regulator adjacent to the intersection before alterations influenced the flow somewhat. It produced a large zone of stagnation in the northwest corner of the intersection, near the floor, but near the roof drew a rapid northward current from well to the south of the center line of the Main West aircourse. This current passed at high velocity over the top of the regulator into the Main North aircourse. As most of the north current passed the east end of the regulator (Figs. 1 and 5) it set up a large eddy near the floor just inbye the regulator. This eddy rotated at moderate speed in a counter-clockwise direction, as viewed from above. Its north limb was about 15 ft. beyond the regulator. The new regulator with a central discharge did not set up any persistent eddies, although there were zones of stagnation near the ribs, at the regulator.

The rush of air out of the Main West aircourse against the west rib in the intersection caused some of the air to flow up along this rib to the roof, then southeast into the south split. Just below this roof current most of the south-split current was flowing southwest. The opposing tendencies of these upper and lower currents could be traced for several feet into the Main South aircourse.

VI. Summary and Conclusions

21. *Summary.*—The effects on the flow of air and the losses involved in its transmission, of cleaning, enlarging, and otherwise improving the aircourses in the high-velocity zone of a large Illinois coal mine are shown in this report.

The mine at which the work was done is ventilated by an electrically-driven centrifugal fan, which is operated blowing. After making a square turn at the bottom of the downcast shaft compartment, the air flows west a few feet, then is divided by a T split into north and south currents. The north branch of the split is artificially regulated. A new regulator with central discharge and adjustable opening was built, and its characteristics were determined.

In general, the physical result of the alterations was to improve the floor and roof profiles, and to increase the cross-sectional area of the aircourses by from 40 to more than 100 per cent, depending on local conditions.

In addition to enlarging the aircourses tributary to the shaft, the shaft outlet was enlarged by cleaning the sump and blasting away some of the lower part of the west shaft wall. Finally, a set of deflecting vanes was installed in the shaft bottom to aid in changing the flow of the air from downward to horizontal.

The technique of former investigations was used throughout. The total quantity determined by traversing the two split currents checked the main current quantity within one per cent, under like conditions of flow. Where simultaneous center velocity pressure readings only were used for determining quantities, the agreement was usually within 2 to 3 per cent. The specific resistance and transmission losses of the split and regulator, shaft bottom bend, and mine as a whole, as affected by the alterations, are reviewed in Table 3, which also indicates the resulting savings, for normal quantities. Cleaning the aircourse adjacent to the shaft reduced the specific resistance of the shaft bottom bend 42 per cent and of the split and

TABLE 3

SUMMARY OF RESISTANCES AND LOSSES

Assuming a total quantity of 110 000 cu. ft. per min. with 56.5 per cent going south

	Split-Bend-Regulator	Shaft-Bottom Bend	Entire* Mine
A. Specific Resistance			
1. Before Alterations	0.55	0.201	2.8
2. After Alterations	0.40	0.116	1.8
3. Per cent Reduction	27.2	42.4	35.7
B. Total Pressure Loss (in. of water)			
4. Before Alterations	0.664	0.243	3.37
5. After Alterations	0.484	0.140	2.17
6. Reduction	0.180	0.103	1.20
C. Energy Loss (air h.p.)			
7. Before Alterations	11.50	4.21	58.4
8. After Alterations	8.39	2.42	37.6
9. Indicated Annual Saving†	$622	$358	$4160‡
D. With Vanes in Place			
10. Total Pressure Loss (in. of water)		0.071	
11. Specific Resistance		0.058	
12. Per cent reduction due to vanes		50.0	
13. Energy loss (air h.p.)		1.23	
14. Indicated Annual Savings†		$238	

*Includes effect of cleaning about 2400 feet of aircourse in addition to the improvements represented in Columns 2 and 3.

†With power costing $100 per horsepower year and 50 per cent overall fan-drive efficiency. No deduction has been made for maintenance costs.

‡This saving is due to underground improvements only. It does not include additional savings from increased fan efficiency.

regulator more than 25 per cent. The estimated annual saving in this combined zone is nearly $1000.

The installation of vanes in the shaft bottom bend so improved the flow of air as to decrease the total pressure loss 0.07 in. of water. This results in an indicated annual saving of more than $200, which is greater than the cost of the vanes in place.

The entire program of improvements, which included cleaning about 2400 feet of aircourse in addition to the work done near the shaft, lowered the mine water gage from 3.3 to 2.1 in., with about the same quantity of air flowing as formerly. This permitted a 20 per cent reduction in fan speed, and resulted in annual savings of over $4000, from lowered velocities and improved airflow alone. Additional savings are realized due to an increase in the overall fan-drive efficiency of from about 43 per cent to 50 per cent.

Such low efficiencies result from the fact that the fan is too large for the mine. A similar fan of one-half the capacity of the present one would be large enough. As judged from the manufacturer's characteristic curves, it would operate at more than 70 per cent efficiency, and would reduce the power consumption nearly one-third.

The characteristics of an adjustable regulator were determined. It produced the maximum energy loss when the area of its opening was about 8 per cent of the total area of the regulator.

In a length of nominally straight aircourse, whose mean cross-sectional area had been increased more than 50 per cent in cleaning, the transmission losses were reduced about two-thirds, quantity for quantity. However, most of this saving is due to reduced air velocities, for at like mean velocities the reduction was only about 24 per cent. The latter saving results from improved lines of flow. It is reflected in a decrease in the ratio $\frac{k}{r}$ from 67.1×10^{-10} before alterations to 50.8×10^{-10} after alterations.

In spite of the improved flow at normal velocities which resulted from the alterations, the slope of the post-alteration loss curves, when losses are plotted logarithmically against quantity or mean velocity, is 0.13 greater than the slope of the corresponding pre-alteration curves. The difference in slope may be due to increased conversion losses, resulting from the more numerous and severe changes in cross-sectional area, which prevailed after alterations.

A study of the velocity and intra-sectional static pressure distributions in section A2 in the Main West aircourse before alterations showed that considerable differences in static pressure existed within the section, and that, in a general way, the static pressure was higher where the velocities were higher. This leads to an uneven distribution of total pressure across the section. Such anomalies are thought to be due to the momentum of the air which prevents it from responding instantly to transverse pressure potentials.

The highest velocities in the Main West aircourse were near the floor. This is characteristic of currents leaving a downcast shaft. Similarly in the Main South aircourse the high velocity focus at section C1 was near the west rib. However, with the improved flow existing in the entry intersection after alterations, the velocity distribution at section C11 was nearly symmetrical, without concentration of high velocities.

The lines of flow were visualized by means of a string indicator. This showed that a small eddy existed in the heel of the shaft bottom, and at the roof of the entry adjacent to the shaft before alterations. Both of these zones were much enlarged after alterations, being marked by stagnation, or eddying at low velocities. An interesting feature of the shaft bottom flow, both before and after alterations, was the pronounced upward component of the air which escaped from the shaft near the ribs. The effect of this was to reduce the size of the stagnant zone at the roof corners, and to yield higher velocities near the roof corners than in the upper central part of the section for several feet from the shaft.

The vanes resulted in a marked improvement in flow by eliminating nearly all eddying and stagnation, and by causing the air to move with higher velocities in the upper parts of the entry.

22. *Conclusions.*—The results of this investigation indicate that where the mean cross-sectional area of aircourses in the high velocity zone of a mine can be increased considerably, say 50 per cent or more, and maintained at moderate expense without the excessive use of obstructing timbers, substantial savings in ventilation costs can be effected by doing so. The major part of the savings come from reduced velocities of flow which ensue when like quantities of air are handled, although a substantial share of them result from improved lines of flow.

Where the size of the entries and the quantities of air being handled are comparable with those represented in this report, a net annual saving approximating the cost of the alterations should result. The savings would increase about as the cube of the quantity in the event of any increase in quantity. By "net annual savings" is meant the cash equivalent of the indicated power saving, minus the cost of maintaining the aircourse in proper condition. As a rule, larger savings can be realized at such features as bends, splits, etc., than in straight entries, although even here large savings can be attained. In fact, the major part of the economies effected in this case occur in the great length of high-velocity aircourse which was cleaned and enlarged.

The installation of a suitable set of vanes in a shaft bottom of the type described here should result in net annual savings in excess of the cost of installation.

Appendix

Some aspects of the interpretation of the data which are not matters of general interest, but which may be useful to other investigators, are given in the following notes:

Note (1).* The mean-velocity pressure in the shaft, rather than that in the entry, was chosen as a basis for comparison because the shaft dimensions remained unchanged. Had the pressure of the mean

*See p. 15.

velocity in the entry been used, the comparison would have been as follows, a quantity of 110 000 cu. ft. per min. being assumed for purposes of derivation:

	Before Alteration	After Alteration
(1) Total pressure loss (in. of water)..	0.243	0.140
(2) Approximate mean cross-sectional area of the Main West Aircourse (sq. ft.)......................	71.4	128.5
(3) Mean-velocity pressure in Main West Aircourse (in. of water)...	0.148	0.0457
(4) Ratio of total pressure loss to mean-velocity pressure........	1.64	3.06

The increase, rather than decrease, in the ratio of line (4) is due, of course, to the sharp reduction in the mean-velocity pressure in the Main West aircourse, which resulted from its great increase in mean cross-sectional area. Thus, instead of reflecting the improvement which actually took place, the ratio indicates an impairment. This illustrates the defect in criteria which are based on mean velocities or velocity pressures, rather than on quantity, in so far as their application to mine air flow is concerned, because in a mine the mean cross-sectional area on the upstream side of a resistance such as a bend, split, or overcast, is seldom equal to that on the downstream side. Furthermore, where changes are made, as in the present case, either one or both of the mean cross-sectional areas may be modified, thereby changing the basis of comparison, as in the foregoing illustration.

The alternative to the use of criteria based on mean velocities or velocity pressure is to adopt one which is based on quantity. The specific resistance is suggested for that purpose.

Note (2). The "specific resistance" of a zone is defined as the ratio of its total pressure loss to the total pressure loss in a zone of unit resistance, with the same quantity of air flowing, per unit of time. A zone of flow is said to develop unit resistance when it causes a total pressure loss of one inch of water for a quantity of 100 000 cu. ft. per min. Thus, the specific resistance $= \frac{i \times 10^{10}}{Q^2}$ where i = total pressure loss (in. of water) and Q = quantity of air flowing (cu. ft. per min). This is an arbitrary adaptation of the Atkinson which is used in England.* As the Atkinson is based on quantity in cubic feet per second it is unsuited to calculations involving quantities in cubic feet per minute.

*Transactions Institution of Mining Engineers, vol. 49, part 3, July 1925.

Since the specific resistance involves only the two terms most commonly used in mine ventilation, that is, quantity in cubic feet per minute and pressure in inches of water, it is easily derived and affords a convenient basis for comparing different resistance zones within a mine, or for comparing the ventilation characteristics of different mines.

Varying directly as the total pressure loss and inversely as the square of the quantity, it is intended to represent a fixed attribute of a given resistance zone, but this will be true only when the total pressure loss incurred by the flow of air through that zone varies as the square of the quantity. Where it varies as some power of the quantity other than 2, the specific resistance will increase or decrease with increasing quantity according to whether the power is greater than or less than 2. However, the deviations from the quantity-squared law are ordinarily not so great as to interfere with the use of the specific resistance as a good approximation over reasonable ranges in quantity.

ILLINOIS COAL MINING INVESTIGATIONS

(Coöperative Agreement)

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†Bulletin 102. The Inflammability of Illinois Coal Dusts: by J. K. Clement and L. A. Scholl, Jr. 1916. *Price, 15 cents.*
†Bulletin 137. Use of Permissible Explosives in the Coal Mines of Illinois: by James R. Fleming and John W. Koster. 1917. *Price, 20 cents.*
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Bulletin 203. Central District Bituminous Coals as Water-gas Generator Fuel: by W. W. Odell and W. A. Dunkley. 1924.
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Bulletin 238. Subsidence Due to Coal Mining in Illinois: by C. A. Herbert and J. J. Rutledge. 1924.
†Technical Paper 246. Water-gas Apparatus and the Use of Central District Coal as Generator Fuel: by W. W. Odell. 1921. *Price, 5 cents.*
†Technical Paper 268. Preparation and Uses of Tar and its Simple Crude Derivatives: by W. W. Odell. 1922. *Price, 15 cents.*
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Technical Paper 304. Water-gas Tar Emulsions: by W. W. Odell. 1923.
Technical Paper 326. Fires in Steamship Bunker and Cargo Coal: by H. H. Stoek. 1923.
Technical Paper 330. Small Hose Streams for Fighting Mine Fires: by L. D. Tracy and R. W. Hendricks. 1924.
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Technical Paper 335. Bituminous Coal as Generator Fuel in Large Water-gas Sets with Waste-Heat Boilers: by W. A. Dunkley. 1925.
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Additional Bulletins on Coal Mining
For the following publications address Director, Engineering Experiment Station, University of Illinois, Urbana, Illinois:

Bulletin 69. Coal Washing in Illinois: by F. C. Lincoln. 1913. *Price, 50 cents.*
Bulletin 88. Dry Preparation of Bituminous Coal at Illinois Mines: by E. A. Holbrook. 1916. *Price, 70 cents.*
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Bulletin 128. The Ignition Temperature of Coal: by R. W. Arms. 1922. *Price, 35 cents.*
Bulletin 196. An Investigation of the Friability of Different Coals: by C. M. Smith. 1929. *Price 80 cents.*
Bulletin 217. Washability Tests of Illinois Coals: by A. C. Callen and D. R. Mitchell. 1930. *Price, 60 cents.*
Circular 5. The Utilization of Pyrite Occurring in Illinois Bituminous Coal: by E. A. Holbrook. 1917. *Price, 20 cents.*
Circular 6. The Storage of Bituminous Coal: by H. H. Stoek. 1918. *Price, 40 cents.*

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